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USE OF TRANSFORMERS IN PRODUCING HIGH POWER OUTPUT FROM HOMOPOLAR GENERATORS

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Abstract

Analysis is presented for systems using high current pulse transformers to exploit the high energy storage capability of homopolar generators or other limited current sources. The stepped-up secondary current can be established either by current interruption when the primary is also used for energy storage or by commutation of current into the primary from a separate storage inductor. For high-power pulse generators the primary insulation and power supply are protected by subsequent crowbarring of the primary. An example is given of a design for matching the NRL homopolar generator with 1.46 mH inductor to a 1-μH, megavolt level inductive pulse generator.

I. Introduction

Pulse power generators using inductive energy storage may have economic promise for applications requiring powers of 10^{11} - 10^{13} W. Studies of opening switches which must be used with inductive storage have shown that it is possible to use carefully made and operated exploding foil fuses as current interrupters[1,2] with high electric fields (of the order of 20 kV/cm) across the fuse. The limitations imposed by the ratio of conduction time to opening time, which is fixed by the nature of the vaporization process, has been overcome by sequentially opening several stages of switches[2] with power multiplication at each stage so that megavolt output pulses are typically obtained. This approach has been extended recently with the TRIDENT pulse generator[3] using larger fuses and requiring currents of the order of 500 kA.

The advent of the explosively driven mechanical switch[4], which can carry these currents for long intervals of time, make it possible to energize the energy storage inductance directly with a current source such as a homopolar generator. One in existence at the Naval Research Laboratory[5] has an energy storage capability of several megajoules and typical current output of 40 kA. To significantly increase the current output from this generator would require additional current-collector brushes. This would be an expensive addition in this case since the use of fiber brushes is required by the high rotational speed. This is an exaggerated case but illustrates the fact that the current output of homopolar generators are limited by brush and contact area.

Any power supply with a limited current capability can nevertheless be used to deliver a large amount of energy by allowing it to energize a sufficiently large inductance. Subsequent switching which produces a change in current allows use of the transformer principle where a change in current in a multiple-turn primary winding is accompanied by a greater change in current in a secondary winding of fewer turns. This procedure was used by Walker and Early[6] to obtain a hundred-fold current step-up in an inductive storage system. The desire to utilize the NRL homopolar generator for the TRIDENT high-power pulser studies mentioned above provides the motivation for this analysis of transformer systems. In circuit design special attention is given to the consequences of high-voltages resulting when the system is used a part of a high-power pulse generator.

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II. Common Store and Transformer

If the energy storage inductance is a coil of many turns, a secondary winding of fewer turns can be coupled to it to become a high-current source for a pulse generator. This concept is illustrated schematically by the circuit shown in Figure 1. In the first stage of operation the homopolar generator, denoted by HPG, energizes a long time-constant coil L_1 with switch S_1 closed. The high current, i_2, in the secondary is established later when S_1 opens to interrupt the primary current. The final, high-power stage is the opening of the switch S_2 causing rapid transfer of the higher current into the load represented by the resistor R_ℓ.

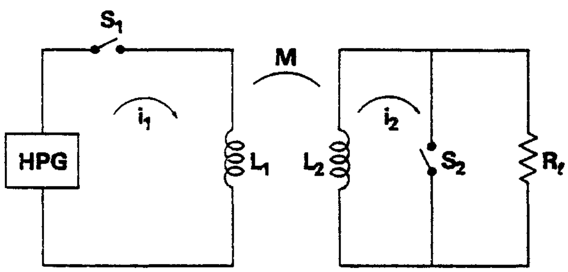

Fig. 1. Circuit for transformer and opening switches with primary energy storage.

If the primary is supplied with a peak current i_o, the stored energy is $W_o=(1/2)L_1\, i_o^2$. The secondary winding need not have a long time constant and secondary currents induced during energizing of the primary will quickly decay to zero. Or, if it is desirable to completely eliminate these precursor currents from the switch S_2, an additional series switch (not shown in the figure) can be incorporated into the circuit between L_2 and S_2.

At the start of the second stage both S_1 and S_2 are closed. The primary and secondary currents have values of $i_1 = i_o$ and $i_2 = 0$. During the interruption of primary current by S_1 the rate of change of secondary flux is

$$M\ (di_1/dt) + L_2\ (di_2/dt) = 0 \qquad (1)$$

where M is the mutual inductance between the two parts of the transformer and L_2 is the self-inductance of the secondary circuit, including the conductors composing S_2. The sign convention for current flow is chosen so that positive currents in both primary and secondary produce magnetic flux in the same direction. The constant flux approximation of Eq. (1) is valid as long as the time constant of the secondary circuit is much greater than the interlude of current change. Integration of Eq. (1) shows that when primary current decays from i_o to 0 the secondary current increases from 0 to a value $i_2=(M/L_2)i_o$, independent of the size and shape of the voltage pulse from the primary switching.

Now with $i_1 = 0$, the remaining stored energy is

$$W_2 = (1/2)\ L_2\ i_2^2 = k^2\ W_o \qquad (2)$$

where $k^2 = M^2/L_1L_2$. If S_1 remains open when S_2 opens, this energy will be delivered to the load, R_ℓ. In this case the primary voltage will be greater than the output pulse by the factor M/L_2.

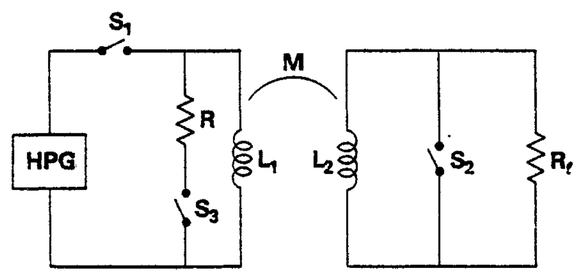

Fig. 2. Crowbar added to circuit of Fig. 1. S_3 Closes before S_2 Opens.

The appearance of high-voltage across the primary can be eliminated by a crowbar, shown as switch S_3 in Figure 2, prior to opening S_2. If R=0 upon opening of S_2 primary flux does not change:

$$L_1\ (di_1/dt) + M\ (di_2/dt) = 0 \qquad (3)$$

The voltage across the load R_ℓ and switch S_2 corresponding to a decrease of secondary flux is

$$\begin{aligned} V_\ell &= -\ M\ (di_1/dt) - L_2\ (di_2/dt) \\ &= -\ (1-k^2)\ L_2\ (di_2/dt) \end{aligned} \qquad (4)$$

and the energy transferred into R_ℓ is

$$W_\ell = \int V_\ell i_2 dt = (1-k^2)\ W_2 = (1-k^2)k^2 W_o \qquad (5)$$

The energy transfer efficiency in this latter case has a maximum of 25% when $k^2 = .5$.

The energy transfer efficiency has been investigated for cases intermediate between those for open-circuit and crowbarred primary by analysis of a

model for the circuit of Figure 2. The model assumes that S_2 is a perfect switch opening instantaneously with no initial primary current and that R_ℓ and R, are constant. Primary and secondary currents were obtained by a straightforward transient calculation. From them the primary voltage

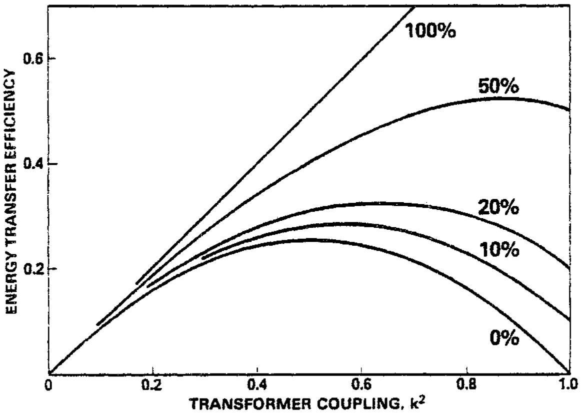

Fig. 3. Energy efficiency against k^2 with resistive crowbar. Curve parameter is peak primary voltage as percent of open-circuit value.

and energy dissipated in R_ℓ were computed as functions of R and k^2. The results are shown in Figure 3 where energy transfer efficiency is shown as a function of k^2 for several primary voltages. The two limiting cases are evident. With open-circuit the efficiency increases as k^2 and with complete crowbar the lower curve is the efficiency predicted by Eq. (5) above.

III. Store Separate from Transformer

Short connections are needed to the TRIDENT pulse generator with its high-voltage switch stages under water. An alternative to placing an existing massive storage coil under water is an entirely separate transformer with its primary current commutated from the storage coil. This concept is shown schematically in Figure 4. In that figure the HPG and storage coil with inductance L_o are shown to the left of the vertical dashed line. The components to the right of the line can be placed in a water tank to facilitate higher-voltage operation. The device represented by this circuit is considered to operate in three stages: slow energizing of the storage inductor, transferring current to the transformer and opening of the final secondary switch.

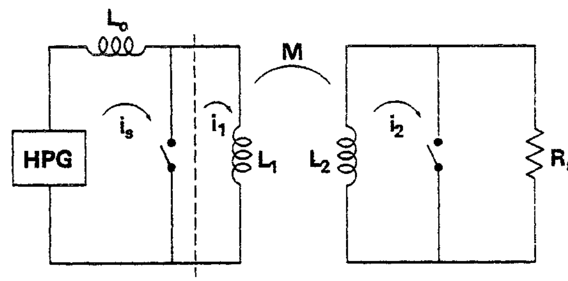

Fig. 4. Circuit for transformer and opening switches with separate energy storage.

Before the transfer stage, the storage inductor is energized by current i_o and energy $W_o=(1/2)L_o i_o^2$ and both switches are closed. If the time constant of the short-circuited secondary is adequately long then Eq. (1) is applicable and secondary and primary currents are related by $i_2 = -(M/L_2)\, i_1$. The voltage appearing across the primary switch as it opens equals the rate of change of the increasing primary flux. It also equals the rate of change of the decreasing flux of the storage inductor.

$$-L_o\,(di_s/dt) = L_1\,(di_1/dt) + M(di_2/dt)$$

$$= (1-k^2)\,L_1\,di_1/dt$$

The current through the primary switch ultimately vanishes, after which $i_1 = i_s$. Integration of the above equation as primary current rises from 0 to a final value, i_1, and the storage current drops from i_o to i_1 results in

$$i_1 = \frac{i_o}{1 + (1-k^2)L_1/L_o} \qquad (6)$$

To avoid unduly high voltages, the primary should be crowbarred prior to opening of the secondary switch. In this case, it was determined earlier that the load voltage is given by Eq. (4). The load power is the product of this voltage and secondary current. By time integrating the power and substituting the relations determined in this section, the energy delivered to the load can be expressed as

$$W_\ell = \frac{k^2\,(1-k^2)\,L_1/L_o}{\left(1 + (1-k^2)\,L_1/L_o\right)^2}\,W_o \qquad (7)$$

This relation is shown graphically in Fig. 5.

Each curve there represents the efficiency as a function of k^2 for some fixed value of the parameter L_1/L_o. The upper envelope for this series of curves is the line $k^2/4$, corresponding to the case $L_o=(1-k^2)L_1$. A maximum efficiency of 25% is approached as k^2 approaches unity and L_1 becomes infinite.

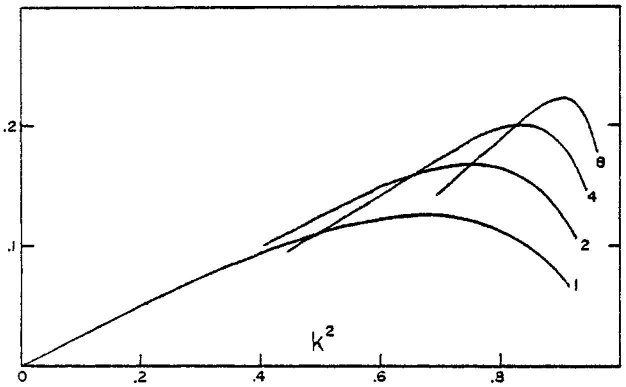

Fig. 5. Energy efficiency against k^2 obtained with circuit of Fig. 4. Curve parameter is L_1/L_o.

IV. HPG-Transformer for TRIDENT

The NRL HPG energizes an existing air-core inductor, L_o = 1.46 mH, which will be coupled by seperate transformer to the 1-μH inductance of the water-insulated TRIDENT inductive pulse generator. A double solenoid design for 20% efficiency with L_1/L_o = 4 and k^2 = 5/6 is illustrated here. Since the primary time constant need not be large, the primary is wound with RG-220/U cable core (2.3 cm diameter). The impulse dielectric strength of this cable is about 450 kV so additional polyethylene must be added to allow a primary-to-secondary voltage approaching a megavolt. The need to simplify connections to the high-voltage pulse former stages dictates that the secondary coil be outside the primary. An iterative procedure of self and mutual inductance calculations determines the 2.2-m diameter and 1.6-m length resulting in L_1= 5.84 mH, M = 223 μH, L_2=10.32 μH and k^2 = .828. The relation $i_2 = -(M/L_2)\, i_1$ implies that net radial forces on primary and secondary are equal and opposite. The primary can be wound on a core for compressive strength. Relatively thin sheet conductors with strong insulating clamps at the output connections will withstand the strain resulting from impulse momentum given to the secondary.

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